

# Confronting Heavy Tau Neutrinos with Neutrino Oscillations

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## Abstract

If the tau neutrino is as heavy as 10 MeV which may have certain astrophysical implications, the neutrino mass pattern is studied so as to accommodate the new oscillation observations. It predicts that the electron neutrino has Marjorana mass around 0.05 eV. A supersymmetric model is described to realize the above scenario.

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There are some motivations for a heavy  $\nu_\tau$ . Cosmologically, 10 MeV  $\nu_\tau$ 's can compose the cold dark matter in a scenario with low re-heating temperature [1]. Theoretically, a 10 MeV  $\nu_\tau$  is predicted in a supersymmetric (SUSY) model which understands the muon mass from the sneutrino vacuum expectation values [2]. One astrophysical implication is that gamma ray bursts may be just the supernova explosions [3]. In this model,  $\nu_\tau$  mixes with other neutralinos slightly. It decays to light gravitino and photon with a very long lifetime  $\sim 10^{13}$  sec. Therefore, distant supernova explosions which emit tau neutrinos look like gamma ray bursts to us.

Neutrino oscillation observations should be considered carefully. The Super-Kamiokande (Super-K) data for the atmospheric neutrino problem (ANP) imply that the  $\nu_\mu$  maximally mixes with  $\nu_x$  ( $x \neq e$ ) with  $\Delta m_{\mu x}^2 \simeq 3 \times 10^{-3}$  eV<sup>2</sup> [4]. And it is claimed that compared to the sterile neutrino, the  $x = \tau$  case is favored [5]. However, Ref. [6] has argued that this claim is not yet reliable, and more careful analysis is needed. Nevertheless, as emphasized in Ref. [7], the  $x = \text{sterile}$  case is not ruled out on its own basis.

The Sudbury Neutrino Observatory (SNO)'s first result [8] for the solar neutrino problem (SNP) makes it clear that mixing among the active neutrinos are essential, although certain involvement of a sterile neutrino cannot be excluded [9]. Recent Super-K's result [10] for the SNP shows that the solutions lie in the large mixing angle (LMA) region with  $\Delta m^2 \simeq 10^{-5} - 10^{-4}$  eV<sup>2</sup> or  $\Delta m^2 \simeq 10^{-9} - 10^{-7}$  eV<sup>2</sup>.

In this Letter, we take  $\nu_\tau$  to be heavy ( $\simeq 10$  MeV). The ANP is explained by introducing a sterile neutrino  $\nu_s$ . The SNP is thus mainly due to the  $\nu_e - \nu_\mu$  mixing. Can this scenario be consistent with neutrino oscillations in detail? There are three light neutrinos,  $\nu_e$ ,  $\nu_\mu$  and  $\nu_s$ . It looks similar to the case of three light active neutrinos which have several forms of the neutrino mass matrix allowed by the neutrino oscillations [11]. However, careful consideration shows that the neutrino mass matrix is almost unique. By introducing a sterile neutrino, naively the pseudo-Dirac mechanism would be expected for the ANP. But this can not explain the SNP, because even if  $\nu_e$  is taken to be degenerate with  $\nu_\mu$  and  $\nu_s$ , the large mixing between  $\nu_e$  and  $\nu_\mu$  can not be achieved. Requiring parameter tunings to be

small, we come up with the following neutrino mass matrix phenomenologically. It in the  $(\nu_e, \nu_\mu, \nu_s)$  basis to the leading order is

$$\mathcal{M}_\nu^{(0)} = \frac{m}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}. \quad (1)$$

Note that the matrix elements (12) and (13) are not necessarily equal. The equality will be exact if the ANP is due to a maximal mixing.

The following mass spectrum is obtained from Eq. (1),

$$m_1 = m_2 = m, \quad m_3 = 0, \quad (2)$$

Two neutrinos are degenerate and one massless. Their mixing matrix is then

$$U = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \end{pmatrix}. \quad (3)$$

The charged lepton mass matrix has been taken to be diagonal at the leading order. Therefore both  $\nu_\mu - \nu_s$  and  $\nu_e - \nu_\mu$  mixing have been fixed to be maximal already, for the ANP and SNP, respectively.

The value of  $m$  is determined by the ANP,

$$m \simeq 0.05 \text{ eV}. \quad (4)$$

The degeneracy of  $\nu_1$  and  $\nu_2$  has to be lift as required by the SNP. Phenomenologically, a small perturbation  $m\epsilon$  can be added to the mass matrix Eq. (1). It splits  $\nu_1$  and  $\nu_2$  with

$$\Delta m_{12}^2 \simeq m^2 \epsilon. \quad (5)$$

$\epsilon \simeq 10^{-2}$  is for the Mikheyev-Smirnov-Wolfenstein [12] solution and  $\epsilon \simeq 10^{-6}$  for the LOW solution.

The fact that the SNP is due to a large mixing instead of a maximal mixing is explained by considering the mixing matrix of charged leptons which was taken as unit matrix at

the leading order. It is then natural to expect the  $\nu_e - \nu_\mu$  mixing angle deviates from  $\pi/4$ ,  $\sin 2\theta_{e\mu} \simeq 1 - \sqrt{\frac{m_e}{m_\mu}} \simeq 0.93$ .

Let us discuss a SUSY model [2,13] which can produce the neutrino mass matrix Eq. (1). The model is a SUSY extension of the standard model. Lepton number violation is introduced so that one of the left-handed sneutrino gets a non-vanishing vacuum expectation value,  $\langle v_3 \rangle \sim \text{few GeV}$  which results in a 10 MeV Majorana mass for the tau-neutrino [2]. In addition, we introduce two heavy ( $N_1$  and  $N_2$ ) and one massless ( $N_3$ ) right-handed neutrino superfields. The relevant superpotential for  $N_1$  and  $N_2$  is generally written as

$$\mathcal{W}_{(1,2)} \sim L_1 H_u N_{1,2} + L_2 H_u N_{1,2} + L_3 H_u N_{1,2} + M_1 N_1 N_1 + M_2 N_2 N_2, \quad (6)$$

where  $L_i$  ( $i = 1, 2, 3$ ) are the SU(2) doublet superfields of leptons,  $H_u$  denotes one of the Higgs fields, and  $M_{1,2}$  are the masses of  $N_{1,2}$ . The basis where the mass matrix of charged leptons is diagonal, is expanded by

$$\begin{aligned} L_e &= \frac{1}{\sqrt{6}}(L_1 + L_2 - 2L_3), \\ L_\mu &= \frac{1}{\sqrt{2}}(L_1 - L_2), \\ L_\tau &= \frac{1}{\sqrt{3}}(L_1 + L_2 + L_3). \end{aligned} \quad (7)$$

In this basis,

$$\mathcal{W}_{(1,2)} \sim L_e H_u N_{1,2} + L_\mu H_u N_{1,2} + L_\tau H_u N_{1,2} + M_1 N_1 N_1 + M_2 N_2 N_2. \quad (8)$$

One observation is that the term containing  $L_\tau$  is useless, because  $\nu_\tau$  is already much heavier. It is natural to expect that the mass sub-matrix of  $\nu_e$  and  $\nu_\mu$  in Eq. (1) comes from the seesaw mechanism given by the other terms in the superpotential Eq. (8), and  $m \sim \langle H_u \rangle^2/M$ .

We assume  $N_3$  couples to  $L_3$  dominantly,

$$\mathcal{W}_3 = c L_3 H_u N_3 \quad (9)$$

with coupling  $c$  being very small,  $c \langle H_u \rangle \sim 10^{-1} - 10^{-2}$  eV. The smallness of  $c$  can be understood if  $N_3$  is a composite particle [14]. In the basis of  $L_e$ ,  $L_\mu$  and  $L_\tau$ ,

$$\mathcal{W}_3 \sim L_e H_u N_3 + L_\tau H_u N_3. \quad (10)$$

Again, the second term is not important for neutrino masses. The first term just generates the (13) entry of the mass matrix Eq. (1). Note that  $N_3$  is almost massless and there is no  $L_\mu - N_3$  coupling. Therefore the texture of neutrino mass matrix Eq. (1) is obtained.

One phenomenologically interesting point of introducing light  $N_3$  in this model is that it interacts with other leptons as

$$\mathcal{W}' \sim \frac{1}{M} L_e L_\mu E_\mu^c N_3, \quad (11)$$

where  $E^c$  denotes the SU(2) singlet charged lepton superfield. Because  $\langle v_3 \rangle \neq 0$ , the above superpotential results in the following interaction,

$$\mathcal{L}' = \frac{v_3}{M} \mu^+ \mu^- \phi_{N_3}, \quad (12)$$

where  $\phi_{N_3}$  is the scalar component of  $N_3$ . Note that after SUSY breaking,  $\phi_{N_3}$  becomes massive. So it decays to  $\mu^+ \mu^-$  with possibly a long decay length. We wonder if this is related to the recent observation of NuTeV Collaboration [15], or can be tested in future experiments.

Experimentally, the neutrino mass scenario in this paper can be tested in the future. Besides the direct measurement of  $\nu_\tau$  mass, the confirmation of the  $\nu_\mu - \nu_\tau$  oscillation for the ANP will be a serious challenge. It is predicted that the electron neutrino has a Majorana mass around 0.05 eV. The neutrino-less double  $\beta$ -decay experiments will probe this value [16]. There is no room for LSND result, but it is compatible with KARMEN experiment. The mixing  $U_{e3}$  can be vanishingly small without affecting the physics discussed in this paper.

When the work was written, we got to know Ref. [17] which reports  $\tau$  appearance in the ANP observation at  $2\sigma$  level. The author is supported in part by the National Natural Science Foundation of China with grant no. 10047005.

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